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Reply on RC4

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Author comment on "Morphological controls on surface runoff: an interpretation of steady-state energy patterns, maximum power states and dissipation regimes within a thermodynamic framework" by Samuel Schroers et al., Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2021-479-AC5, 2021

We thank Ref.2 for his thoughtful analysis.

First, we would like to address his/her two principal concerns regarding the focus of the study, which we believe are due to the broad range of applicability of the theory. We are thankful for these comments (as also previously made by K. Beven) and we intend to present the theory and its application in a clearer way in a revised version of the manuscript.

We focus in this paper on the analysis of surface runoff from a thermodynamic perspective. Therefore, we depart from the first law of thermodynamics (Eq. 1), which we apply in the subsequent equations for balancing energy fluxes of an open thermodynamic system. As mentioned in the introduction and by the second law of thermodynamics, entropy can only increase. This is constrained by the Carnot limit, which is the maximum amount of work that can be extracted from a heat engine with fixed boundary conditions. For a dissipative system with non-fixed boundaries, which is the case for most natural systems, there exists a trade-off between driving gradient and flux, resulting in a maximum power limit (Kleidon, 2016). We therefore hypothesize that driving gradients and fluxes of surface runoff systems evolve into a state of maximum power and we argue that the spatial organization of structure and dissipative processes is a result of this evolution.

For the surface runoff system of our study this means that the potential energy, which is added by rainfall on different topographic levels needs to be depleted as fast as possible. This can be achieved by maximizing runoff, more specifically, the system maximizes the kinetic energy of the runoff. While doing so, the runoff system spatially organizes in a way that loss of energy is minimized along the flow path, but overall, it maximizes dissipation through faster depletion of the driving gradient of potential energy. This interplay manifests as global maximization of free energy loss in time (dissipation) by local minimization of free energy loss in space (friction).

As the distribution of free energy gradients is key for the resulting fluxes, we show from the results of Emmett’s experiments that measured surface runoff on hillslopes does surprisingly not strictly follow this theory, but results in a maximum of potential energy somewhere along the flow path. This phenomenon stands energetically in contrast to a river system and occurs because downslope mass accumulation over-compensates the declining geopotential. We propose that this switch in the downslope potential energy gradient relates to the transitional character of surface runoff, and we think that there is a critical level of flow accumulation for surface runoff to be classified as a strictly Hortonian surface runoff system, which can be represented by Fig. 1 of the manuscript.

Regarding the second point raised by the Referee, we believe that the process of organization is transient and different adjustments of structure manifest after different time periods and on different scales. On a larger scale much more total work is needed to form typical hillslope profiles, resulting in geological time scales of transient adjustments of hillslope or river profile adjustments until reaching a thermodynamic equilibrium. On a small-scale hillslope plot the same underlying process of maximization of entropy leads much faster to the formation of structure, typically during seasonal if not event time scales. For testing our theory, large scale adjustments would need to be simulated in a laboratory (e.g., Singh et al., 2015) but hillslope plot-scale adjustments can be observed from experiments on real hillslopes. We therefore consider both, sect. 2 and sect. 3 equally important to show different aspects of the same underlying physical process. However, we agree with the Ref. that the current manuscript would benefit from a clearer explanation of the similarities and differences of both sections as well as pointing out the common objectives.

This applies also to the last point raised by the Referee regarding the use of a model, which distributes surface runoff into rill- and sheet flow. As the minimization of energy loss per unit volume in flow path direction results in a structured surface we investigated surface runoff experiments where adjustment of structure by formation of rills was observed. As the resulting rill flow velocities were measured and the sheet flow velocities back calculated from total measured discharge, the model allows an estimation of the spatial distribution of free energy gradients and fluxes. The results could then be used to test our hypothesis that surface runoff on hillslopes evolves into a state of maximum power. Although we agree that the two calibrated experiments are statistically not significant for a definite conclusion, further modelling would imply an additional layer of complexity in this study and was intentionally left for future investigation. We thank Ref.2 for his comments on our study.

References

Singh, A.; Reinhardt, L.; Foufoula-Georgiou, E. (2015): Landscape reorganization under changing climatic forcing: Results from an experimental landscape, Water Resour. Res., 51, 4320–4337, doi:10.1002/2015WR017161.